DARK MATTER SEARCH WITH DIRECTION SENSITIVE SCINTILLATOR

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A direction sensitive dark matter detector using organic crystals is being developed. It exploits the anisotropic scintillation efficiency of organic crystals with respect to the direction of nuclear recoils relative to crystallographic axes. A variation of about 7% was observed in the scintillation efficiency of carbon recoils in a stilbene crystal for recoil energies of 30 keV to 1 MeV. We have performed a pilot experiment at Kamioka to prove the feasibility of this method.

1. Introduction

It is believed that the galactic halo is composed of WIMP dark matter. WIMPs could be directly detected by measuring the nuclear recoils produced by their elastic scattering off nuclei in detectors[1], and the most convincing signature of the WIMPs appears in the directions of nuclear recoils because the earth's velocity through the galactic halo is large ($\sim$ 230km/s). Hence, detectors sensitive to the direction of the recoil nucleus have a great potential to identify WIMPs.

Now, we are developing organic crystalline scintillators as direction sensitive dark matter detector[2]. In this paper, we report on anisotropic scintillation property of stilbene crystals and its application to the dark matter search.

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2. Direction Sensitive Scintillator

It is known that scintillation efficiency of organic crystals to heavy charged particles depends on the direction of the particles with respect to the crystallographic axes[3]. This property could be applied to a direction sensitive WIMPs detector[4].

We adopted stilbene crystal scintillators, because of its relatively high light yield (30% of NaI), and the anisotropy — known to be about 20% for 6.5-MeV α particles[5]. However, the recoil energy given by WIMPs is much lower.

Therefore, we measured the angle and energy dependence of the scintillation response of carbon recoils in a stilbene crystal in the low energy region with nuclear recoil events caused by elastic scattering of neutrons. In order to obtain high statistics and wide neutron energy range, two neutron sources, $^{7}\mathrm{Li}(p,n)^{7}\mathrm{Be}$ and $^{252}\mathrm{Cf}$, were employed. The $^{7}\mathrm{Li}(p,n)^{7}\mathrm{Be}$ source run was performed at 3.2-MV Pelletron accelerator of the Research Laboratory for Nuclear Reactors at Tokyo Institute of Technology. Pulsed proton beam interacted with a thin lithium target, and pulsed neutrons were produced by the $^{7}\mathrm{Li}(p,n)^{7}\mathrm{Be}$ reaction. Details of the experimental setup are given in Ref. 2.

Stilbene crystals form monoclinic systems and the crystallographic axes are called a, b and c as shown in Fig. 1. The axis perpendicular to a–b plane is called c' which can be easily known since the crystal is cleaved along a–b plane.

A $2 \times 2 \times 2\,\mathrm{cm}^3$ stilbene crystal was used as the target. The energies of incident and scattered neutrons were measured by the time-of-flight (TOF) method, and the recoil energy E_R was determined by kinematics.

The scintillation efficiency for carbon recoils relative to that for electrons with $\theta = 0°$ and $90°$ are shown in Fig. 1. The variation of the scintillation efficiency in θ is about 7% over the measured energy region, $E_R = 30\,\mathrm{keV}$–$1\,\mathrm{MeV}$. The scintillation efficiency is maximal in the direction perpendicular to c' axis namely at $\theta = 90°$, and is minimal in the direction parallel to c' axis namely $\theta = 0°$. No significant ϕ-dependence is observed. This behavior is consistent with the result of proton recoils[6] and of high energy charged particles[5].

3. Application to WIMPs Detector

Let us discuss the directionality signature by considering the expected signal counting rate. Assuming the WIMP halo is an isothermal sphere, the

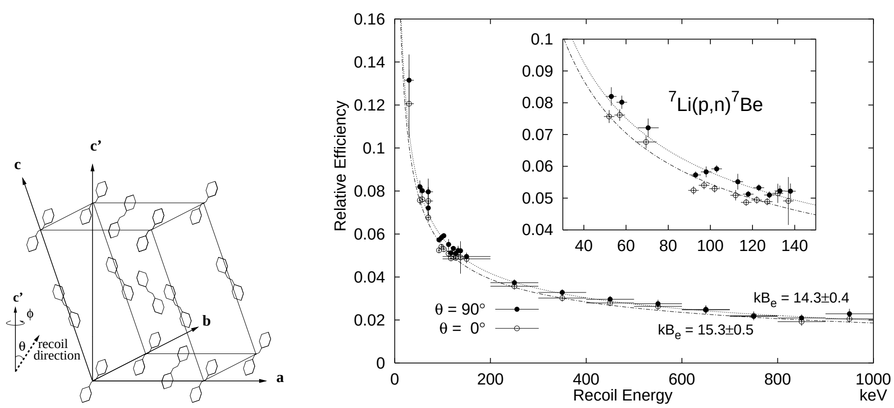


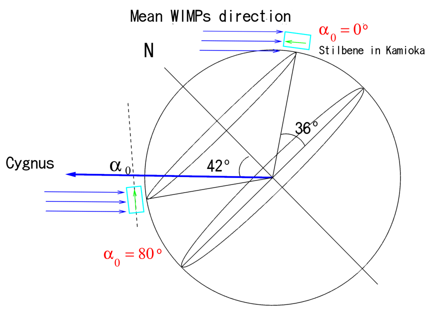
Figure 1. The measured scintillation efficiency relative to that for electrons with $\theta = 0°$ and $90°$ recoils ($\phi = 0°$). The inset is the results of the ^{7}Li$(p,n)^7$Be source run. Horizontal error bars represents selected recoil energy region for calculating the efficiency. The definition of the recoil angles θ and ϕ are shown in the left along with the schematic drawing of the stilbene crystalline lattice where a stilbene molecule is drawn smaller than reality. θ is the angle with respect to the c' axis and ϕ is the angle around the c' axis.

WIMPs mainly come from the direction of the Cygnus whose polar zenith angle is about 42° in the heliocentric frame. If we perform the experiment in Kamioka Observatory at 36° 25' 30" N and 137° 18' 32"E, a suitable arrangement for the stilbene crystal is to install the detector with the c' axis in parallel to the horizontal plane and towards the North as illustrated in Fig. 2. In that case, the mean incident angle of the WIMP with respect to c' axis, α_0, varies between 5° and 78° within a sidereal daily period neglecting the effect of aberration of WIMPs for simplicity.

An example of the variation of the expected counting rate in 4-6 keV energy window calculated by the Monte Carlo method as of December 1st 2003 JST is shown in Fig. 2. The effect of the motion of the earth is fully taken into account using NOVAS[7].

4. Pilot Experiment in Kamioka Observatory

A pilot dark matter search experiment to prove the feasibility of the method was carried out in Kamioka Observatory. The schematic view of the experimental setup is shown in Fig. 3. The ϕ50 mm × 50 mm (116 g) cylindrical stilbene crystal is viewed by two Hamamatsu R8778MOD low background PMTs through two Horiba low background NaI(Tl) active shields. Self coincidence of two PMTs are required and both PMTs are cooled down



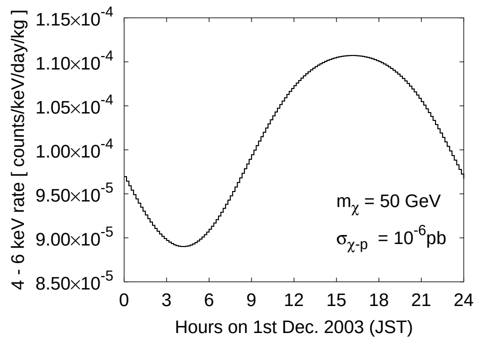


Figure 2. left: Schematic drawing of the experimental approach method mentioned in the text. right: The expected signal variation of the counting rate of WIMP induced carbon recoil in an stilbene crystal with c' axis parallel to north-south direction as of December 1st 2003 (JST). The parameters that we used in the calculation are $\rho_0 = 0.3$ GeV/cm^3, $v_0 = 220$ km/sec, WIMP-proton spin independent cross section $\sigma_{\chi-p} = 10^{-6}$ pb, and $m_\chi = 50$ GeV

at about -7℃ to reduce dark current further. The detector assembly is shielded with 10cm OFHC copper, 15 cm Lead, and 20cm polyethylene. The EVOH sheets[8] are formed into air tight bags filled with nitrogen gas for purging the radon gas. As mentioned above, the whole setup is laid with the c' axis of the crystal parallel to the north-south direction.

With the detector system, we started the measurement in October 25, 2003 and it was halted in December 11, 2003. The obtained count rate of 4-6 keV energy window for every one hour during the measurements are shown in Fig. 4. Since the background level is as high as 2000 counts/keV/day/kg, no modulation signal was found in the results.

5. Discussions and Future Prospects

It is obvious that rather high background rate due to the radioactivity in PMTs limits the sensitivity. Although the introduction of NaI(Tl) was turned out to be somewhat effective, it is not sufficient to deal with the problem. Therefore, in order to overcome the difficulties, highly radio-pure, high quantum efficiency, high gain photon detector is indispensable. Recently, the technology to produce avalanche photodiodes (APDs) has improved significantly, and comparable or better performances of APDs to those of PMTs are obtained with various scintillators[9]. Hence, we are going to develop APDs with low background materials.

Another disadvantage of the current method is the atomic (i.e.^{12}C)

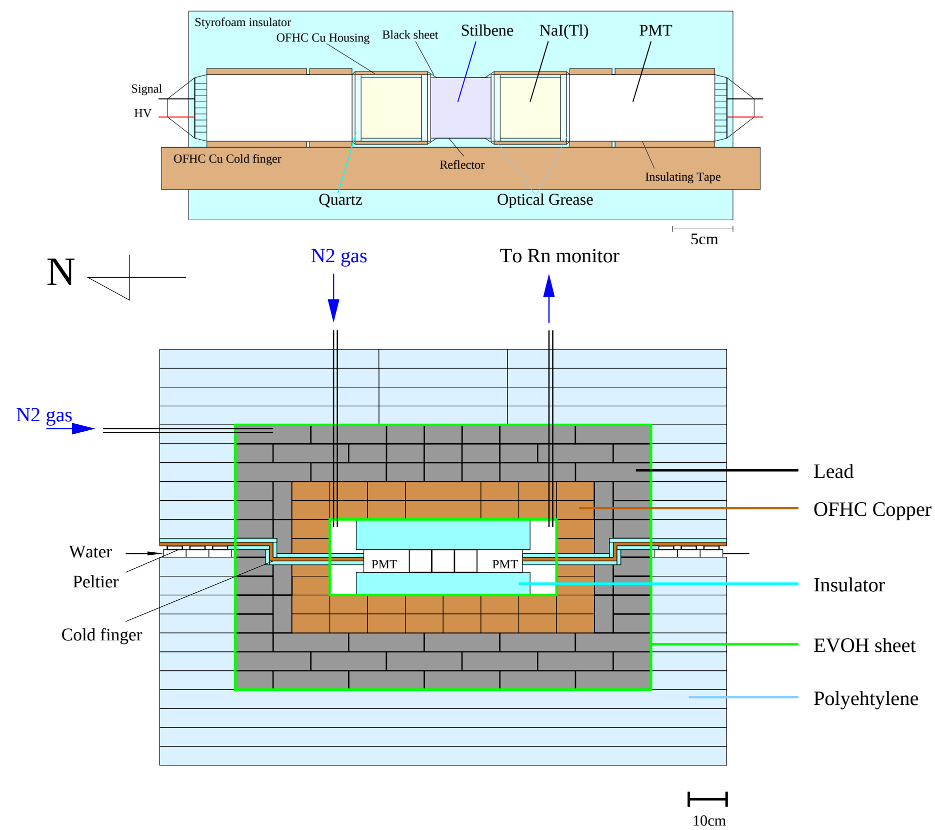


Figure 3. Schematic view of the detector and the shields.

weights. Generally, the SI cross section is proportional to A^2. On the other hand, the SD cross section is proportional to the nuclear spin factor $\lambda^2 J(J+1)$ and ^{19}F is considered to be the best nucleus to search for the SD interaction[10]. Therefore, we focus on fluorine loaded organic crystals. We are now processing the growth of single crystals of octafluolonaphthalene ($C_{10}F_8$).

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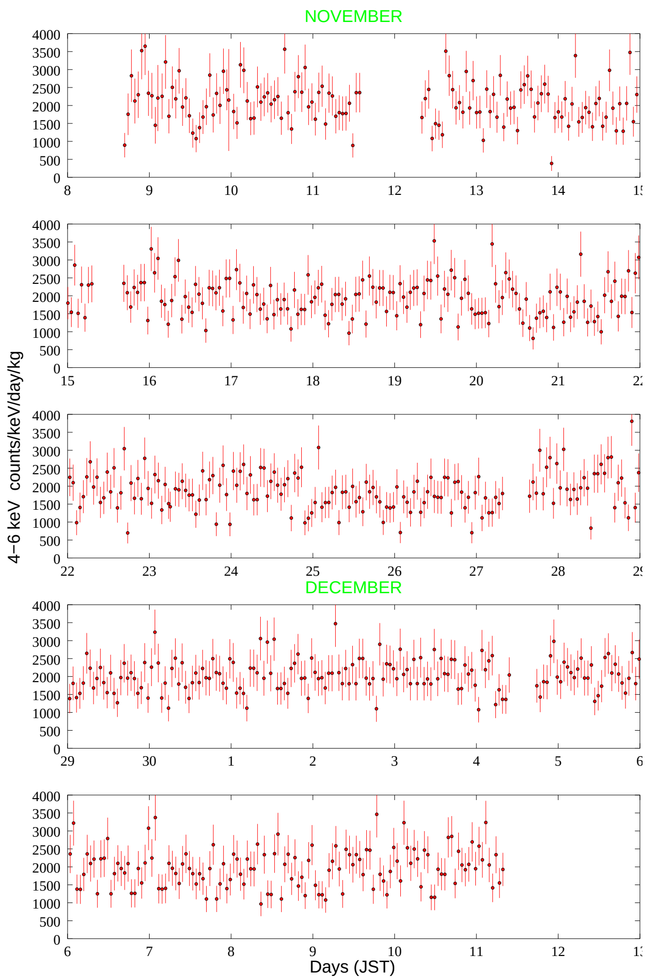

Figure 4. The obtained event rates for 4-6 keV during the measurements.

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